Operational results of a 1,200-gpm passive bioreactor for metal mine drainage, West Fork, Missouri

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ABSTRACT: An active underground lead mine produces water having a pH of 8.0 with 0.4 to 0.6 mg/L of Pb and 0.36 mg/L of Zn. This water is pumped at the rate of 1,200 gpm (0.076 m^3/s) into a five-cell, bioreactor system covering about 5 acres (2 hectares). The gravity flow system is composed of a settling basin followed by two anaerobic bioreactors arranged in parallel which discharge into a rock filter polishing cell that is followed by a final aeration polishing pond. The primary lead removal mechanism is sulfate reduction/sulfide precipitation. The discharge has met stringent in-stream water quality requirements since its commissioning in 1996. However, there have been startup and operational difficulties. The system was designed to last about 12 years, but estimates suggest a much longer life based on anticipated carbon consumption in the anaerobic cells.

1 INTRODUCTION

The West Fork Unit is an underground lead-zinc mine purchased by the Doe Run Company from Asarco in 1998 that discharges water from mine drainage to the West Fork of the Black River (West Fork) under an existing NPDES permit. The West Fork Unit is located in Reynolds County in central Missouri, in the New Missouri Lead Belt, about three hours from St. Louis.

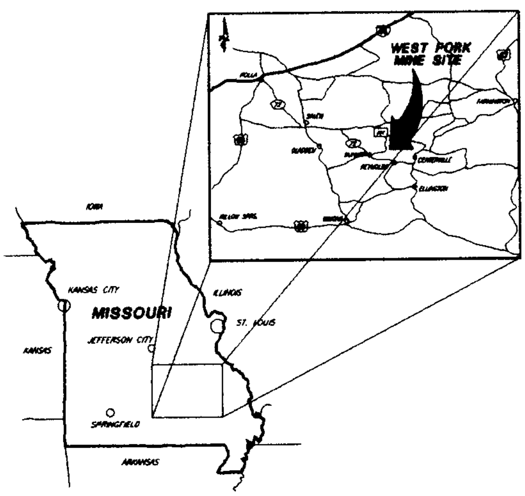

Figure 1 - Site Location

Flow rates in West Fork vary from about 20 cubic feet per second (cfs) to more than 40 cfs (0.56 to 1.13 m^3/s). Water quality is relatively good, despite being located in an area with naturally high background levels of lead due to the bedrock geology. The mine discharges about 1,200 gpm (2.7 cfs or 0.076 m^3/s) on the average or about 10 percent of the total flow in West Fork.

The adoption of water quality-based discharge limits, in its NPDES permit issued in October 1991, prompted Asarco to evaluate treatment methods for metal removal. Evaluations of alternative treatment processes determined that biotreatment methods were feasible and cost less than half as much as active sulfide precipitation. The goal of the water treatment project was to ensure that the stringent water quality-based limits in the permit would be consistently met.

Since 1987, a group from Knight Piésold and Co. and the Colorado School of Mines has been active in developing passive treatment methods for metal-mine drainages. The primary treatment method is through the generation of hydroxides and sulfides through microbial metabolism. The biogeochemical principles are summarized in Wildeman, et al. (1995), and Wildeman and Updegraff (1998). The design principles are explained in Wildeman, Brodie, and Gusek (1993). In the case of the West Fork Unit, biotreatment consists of two stages:

1. An anaerobic unit that generates sulfide through sulfate reduction and is responsible for the lead removal.
2. An aerobic unit that is a rock filter/wetland. This unit is responsible for removing dissolved organic matter and excess sulfide from the effluent from the anaerobic cell. The aerobic unit also reoxygenates and polishes the water before it enters the river.

Extensive laboratory, bench-scale, and pilot scale tests were made on the anaerobic unit. These are described in Wildeman, et al. (1997), and Gusek, et al. (1998). The design and permitting of the system are also discussed in Gusek, et al. (1998), and Wildeman, et al. (1999). This paper concentrates on the operation of the full-scale system since its start in 1996.

2 SYSTEM DESCRIPTION

The system was designed based on the performance of the pilot-scale reactor and the interim bench scale studies. The large-scale system was estimated to cost approximately $500,000 and required about three months of construction time. Operational costs include water quality monitoring as mandated by law. No additional costs for reagents are incurred; since the system uses gravity flow, moving parts are few and include valves, minor flow controls, and monitoring devices. Based on carbon depletion rates observed in the pilot system, the anaerobic cell substrate life was projected to be greater than 30 years; the full-scale biotreatment system should be virtually maintenance-free. Should mine water quality deteriorate, the full-scale design included a 50-percent safety factor.

The biotreatment system is composed of five major parts: a settling pond, two anaerobic cells, a rock filter, and an aeration pond (Knight Piésold, 1997). The system is fully lined. The design was also integrated into the mine's pre-existing fluid management system.

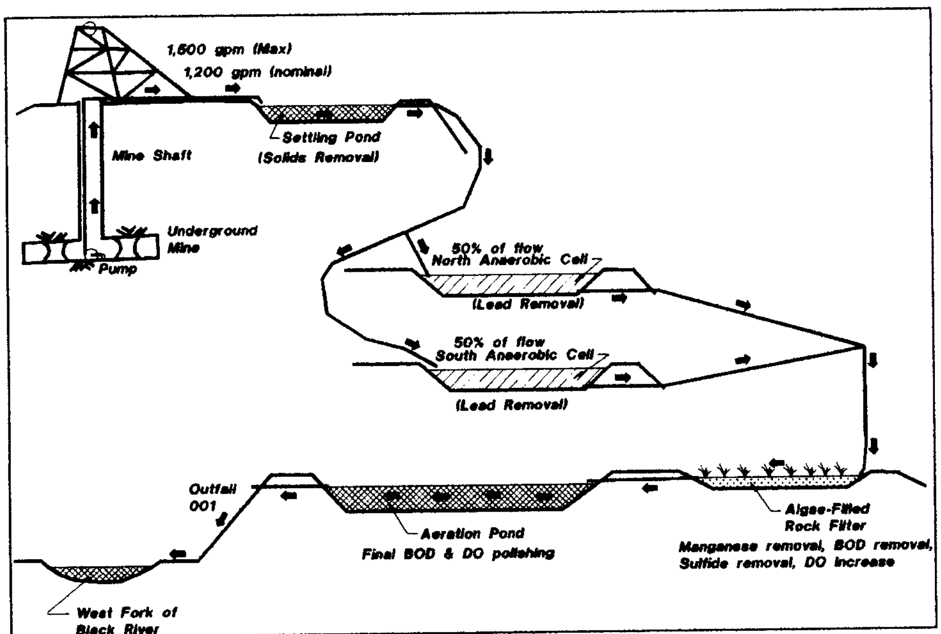

Figure 2 - System Configuration

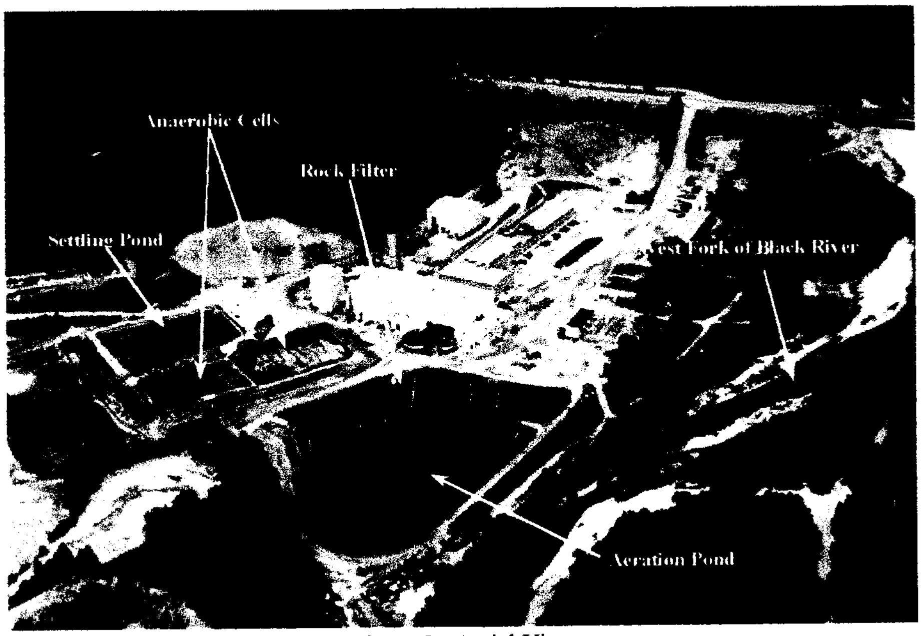

Figure 3 - Aerial View

A rectangular-shaped, 40-mil HDPE-lined settling pond has a top surface area of 32,626 ft^2 (3,030 m^2) and a bottom surface area of 20,762 ft^2 (1,930 m^2). The sides have slopes of 2 horizontal to 1 vertical (2H:1V). The settling pond is nominally 9.8 ft (3 m) deep. It discharges through valves and parshall flumes into the two anaerobic cells.

Two anaerobic cells are used, each with a total bottom area of about 14,935 ft^2 (1,390 m^2) and a top area of about 20,600 ft^2 (1,930 m^2). Each cell is lined with 40-mil HDPE and was fitted with four sets of fluid distribution pipes and three sets of fluid collection pipes, which were subsequently modified (see Start Up discussion). The distribution/collection pipes were connected to commonly shared layers of perforated HDPE pipe and geonet materials sandwiched between layers of geofabric. This feature of the design was intended to allow control of sulfide production in hot weather by decreasing the retention time in the cell through intentional short circuiting.

The spaces between the fluid distribution layers were filled with a mixture of composted cow manure, sawdust, inert limestone, and alfalfa, referred to hereafter as "substrate." The total thickness of substrate, piping, geonet, and geofabric was about 6 feet (2 m). The surface of the anaerobic cells was covered with a layer of crushed limestone. Water treated in the anaerobic cells flows by gravity to a compartmentalized concrete mixing vault and thereafter to a rock filter cell. The gravity-driven flows can be directed upward or downward.

The rock filter is an internally bermed, clay-lined shallow cell with a bottom area of about 63,000 ft^2 (5,900 m^2) and a nominal depth of one foot (30 cm). It is constructed on compacted fill that was systematically placed on the west side of a pre-existing mine water settling pond. Limestone cobbles line the bottom of the cell, and the cell is compartmentalized by limestone cobble berms. The discharge from the rock filter flows through a drop pipe spillway and buried pipe into a 40-mil HDPE-lined aeration pond. The aeration pond surface covers approximately 85,920 ft^2 (8,000 m^2). The aeration pond discharges through twin 12-inch (30-cm) HDPE pipes into a short channel that leads to monitoring outfall 001 and thence into West Fork.

After the water pumped from the underground mine enters the settling pond, all flows are by gravity.

3 START-UP EXPERIENCE

Bench-scale test results suggested that the anaerobic cells be incubated with settled mine water for about 36 hours or less before fresh mine water was introduced at full flow to minimize initial levels of BOD, fecal coliform, color, and manganese. For about two weeks, pumps recycled the water within the two anaerobic cells. Based on data collected in field, and subsequent laboratory confirmation, the water from the anaerobic cells was routed to the tailings pond for temporary storage and later treatment and release. At that point, the rock filter and aeration ponds were brought on-line. In the meantime, the mine discharged according to plan through an overflow pipe from the settling pond as it had during construction of the other components.

After about six weeks of full-scale operation, the apparent permeability of the substrate was found to be lower than expected and the system was operating nearly at capacity. The system had been designed so that either of the two anaerobic cells could accept the full flow amount on a temporary basis in case maintenance work required a complete cell shutdown.

Research found that H_2S gas, generated by the sulfate-reducing bacteria, was being retained in the substrate in the anaerobic cells; this created a gas-lock situation that prevented full design flow. A temporary solution was obtained by periodic "burping" of the cells using the control valves. However, the "burping" had to be performed at 24-hour intervals, and it was determined that this solution was too labor-intensive.

The sulfide gas lock problem was investigated in December 1996 by installing vent wells in the substrate and measuring the gas pressures. Observations indicated that the gas was a factor in apparent short circuiting of the water passing through the cell. The layered geotextiles (geonet and geofabric), originally intended to promote horizontal flow, appeared to be trapping the sulfide gas beneath them and vertical flow was being restricted. The permeability of the substrate itself was for the most part unaffected. However, construction practices in the south anaerobic cell could have contributed to the situation. Here, a low ground bearing bulldozer was used to place substrate in nominal 6-inch (15-cm) lifts. This could have created a layering effect that may have trapped gas as well. Substrate layers in the north anaerobic cell were placed in a single lift, and no layering effect was observed during subsequent excavation. It is noteworthy that the mid-cell geotextiles had not been a feature of the pilot test cell design.

The first phase of a permanent solution was implemented with a trenching machine that ripped through the geonet/geofabric layers in the south anaerobic cell. This disrupted the gas-trapping situation. Subsequently, the substrate from the entire south anaerobic cell was excavated and the cell refilled without the geotextiles in June 1997. Identical action was taken on the north anaerobic cell in September 1997. These actions have solved the gas lock problem.

4 MAINTENANCE EXPERIENCE

Although this is technically a passive treatment system, when one considers trying to direct the flow of 1,200 gpm (0.076 m^3/s) through approximately 3,930 yd^3 (3,000 m^3) of material there is certain to be some hydraulic problems. In addition, the design of the anaerobic cells made provisions for the water to bypass portions of the cells during the summer to eliminate excess buildup of sulfide in the cell effluent. In the summer of 1997 and 1998, operation of the system included by-passing some portions of the cell to maintain lower sulfide concentrations. However, when this was tried, short-circuiting within the cells and plugging of the substrate made maintenance during the summer more extensive than during the winter.

Perhaps the most troublesome maintenance issue was that a combination of sediment in the mine water along with algae buildup on the cell surfaces would block the infiltration of water into the cells.

This would necessitate periodically draining the cells and rototilling the top of the substrate so as to break up the accumulation cake. Often at the same time as a cell was tilled, water would be back-flushed through the discharge pipes to dislodge precipitate accumulation. When such maintenance was done, the rock filter would still receive discharge. It has proved to be an effective buffer between the cells and the discharge pond. This maintenance cycle of tilling and back-flushing had to be done almost once a month during the summer of 1998. During the winter, buildup was not as extensive and maintenance of the cell surfaces was less frequent. Currently, schemes are being investigated to try a drastic reconditioning of the cells to permanently increase the hydraulic conductivity of the anaerobic cells.

Other than repairing a bubble that appeared under the liner of the aeration pond, there has been no maintenance needed on the rock filter and the aeration pond.

5 OPERATIONAL RESULTS

5.1 *The Anaerobic Cells*

The average influent water quality can be compared with discharge water quality (Table 1) during the June through November 1997 period. Discharge levels of Pb and other metals were reduced substantially from average influent levels. For Pb, the level was reduced from a typical average of 0.40 mg/L to between 0.027 and 0.050 mg/L. Zn, Cd, and Cu effluent concentrations were also reduced.

Table 1 - West Fork Mine Water Quality Data

Parameter	Typical Average Influent Water Quality in mg/L	Range of Water Quality Discharge in mg/L (June - November 1997)
Pb	0.4	0.027 - 0.050
Zn	0.36	0.055 - 0.088
Cd	0.003	<0.002
Cu	0.037	<0.008
Oil and Grease	--	<5.0
H_2S	--	0.011 - 0.025
Total Phosphorus	--	<0.05 - 0.058
Ammonia as N	0.52	<0.050 - 0.37
Nitrate and Nitrite	2	<0.050 - 1.7
True Color	--	10 - 15
BOD	1.7	<1 - 3
Fecal Coliform	—	<1 - 2
pH	7.94	6.63 - 7.77
TSS	—	<1 - 4.2

More extensive analysis of the operational data from June 1997 through June 1999 has shown some interesting results. The plumbing system in the anaerobic cells was designed to run the cells upflow or downflow, to use a portion of the cell when sulfide production became too high, and to be back-flushed in case precipitation occurred in the discharge line. All three features have been used. The cells have been run in the upflow direction during the first winter so that the substrate compaction that occurred during the summer could be relieved. The three levels of discharge pipes are routinely monitored for sulfide production, and the valves are adjusted accordingly to eliminate excess sulfide. In the summer, these adjustments become more difficult as attempts are made to only use portions of the cells. In addition, the cells are routinely back-flushed to maintain good circulation of mine water through the cells.

By operating the anaerobic cells in this fashion, over four seasons from July 1997 to July 1998, the average concentration of 40 analyses of total Pb in the water entering the cells is 0.45 and the average concentration of Pb in the water exiting the cells is 0.085. Results for zinc are not as extensive. From March 1998 to November 1998, the average concentration of 10 analyses of total Zn in the water entering the cells is 0.44 and the average concentration of Zn in the water exiting the cells is 0.102.

Within the anaerobic cells, production of enough sulfide has never been a problem. During the summers of 1997 and 1998, sulfide concentration in discharges from some portions of the cells routinely exceeded 12.0 mg/L, the upper quantitation limit of the analytical procedure. This correlates with the pilot cell results where, during the two summers in which it operated, sulfide concentrations reached 20 mg/L. According to Wildeman, et al. (1997), at this level of sulfide concentration, the production of sulfide in the anaerobic cells is about 2 moles sulfide per cubic meter per day. As expected, during the winter, concentrations of sulfide in the cell effluent are lower. However, even during the months of December, January, and February, sulfide concentrations in the discharge from some portions of the cell were between 2.0 and 7.7 mg/L. These concentrations have been higher than the average of 0.3 mg/L of sulfide that was found during the winter the pilot cell operated (Wildeman, et al., 1997).

5.2 *The Rock Filter*

Of the five parts of the system, the operation of the rock filter has been the most interesting. It operates as a natural wetland where water of a depth of 1 to 2 feet (30 to 60 cm) meanders through the limestone cobbles. Flora and fauna have thrived in this ecosystem. It has served the important function of cleansing the excess sulfide in the water that is leaving the anaerobic cells. From July 1997 to September 1998, the average of 55 analyses of sulfide concentration in the water entering the rock filter is 3.3 mg/L. In 55 analyses of sulfide in the rock filter effluent, sulfide was detected in the water 20 times and none of these were above 0.25 mg/L.

Because the water entering the rock filter contains a significant concentration of sulfide, a unique ecosystem of algae and bacteria have developed in this area. In the summer of 1997, red algae/bacteria started to develop in this influent area and have persisted. In addition, a white scum has developed in this area. Indeed, the rock-filter influent area looks like a pool of the primordial soup. During the summer of 1997, when high levels of sulfide were entering the rock filter, the water would develop a milky white colloidal suspension that would persist throughout the wetland system. This milky suspension had diurnal characteristics. It would be more persistent in the morning and sometimes clear up during the day. In the summer of 1998, this milky suspension was not as evident even though the concentrations of sulfide entering the rock filter were sometimes higher. Vegetation in the rock filter was much more lush in the second summer. The speculation is that this milky suspension is colloidal sulfur. If it is, then this form of wetland ecosystem removes it.

Besides removing sulfide from the water, the rock filter also plays a significant role in further reducing the concentration of lead in the water. Over four seasons from July 1997 to July 1998, the average concentration of 40 analyses of total Pb in the water entering the rock filter is 0.085 and the average concentration of Pb in the water exiting the rock filter is 0.050. The mechanism for lead removal in the rock filter is not known.

6 CONCLUSIONS

In the introduction to this paper it was stated that the biotreament system should be virtually maintenance free. That has not been the case with the anaerobic cells. Keeping these cells from clogging has required periodic rototilling and back-flushing. Because attempts were made during the summer to use only a portion of the two cells, maintenance has been more extensive at this time than during the winter. Nevertheless, these cells have performed according to design and have been effective at removing lead from the mine water. Because of this necessary maintenance, the design of the plumbing system to include back-flushing, upflow and downflow, and use of only a portion of the cell has been particularly advantageous.

The need for the rock filter has been found to be essential. Its operation has shown some surprises. The presence of sulfide in the water has caused a unique ecosystem that effectively removes this constituent from the water. The removal of sulfide is more important in the summer. The rock filter also removes a significant amount of lead. The removal mechanism is unknown.

7 ACKNOWLEDGMENTS

The foresight and subsequent commitment of ASARCO and the Doe Run Co. to this type of treatment is most appreciated.

8 REFERENCES

Gusek, J.J., Wildeman, T.R., Miller, A., and Frickem, J., 1998. The challenges of designing, permitting, and building a 1,200 gpm passive bioreactor for metal mine drainage, West Fork, Missouri. In: *Proceedings of 15th Annual Meeting of American Society for Surface Mining and Reclamation*, pp. 203-212.

Wildeman, T.R., Gusek, J.J., Cevaal, J., Whiting, K., and Scheuring, J., 1995. Biotreatment of acid rock drainage at a gold-mining operation. In: *Bioremediation of Inorganics*, R.E. Hinchee, J.L. Means, and D.R. Burris, Eds., Battelle Press, Columbus Ohio, pp. 141-148.

Wildeman, T.R., Gusek, J.J., Miller, A., and Frickem, J., 1997. Metals, sulfur, and carbon balance in a pilot reactor treating lead in water. In: *In Situ and On-Site Bioremediation*, Volume 3. Battelle Press, Columbus, OH, pp. 401-406.

Wildeman, T.R., and Updegraff, D., 1998. Passive bioremediation of metals and inorganic contaminants. In: *Perspectives in Environmental Chemistry*, D.L. Macalady, Ed., Oxford University Press, New York, pp. 473-495.